TITLE: Relief Valve Sizing for a Nitrogen Precool of the 30" Magnet

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OBJECT: To determine the maximum pressure achieved in the helium dewar due to a sudden, massive loss of insulating vacuum, during nitrogen precool.

General Assumptions

1. The heat flux removed due to nitrogen or ambient air cooling and/or oxygen condensing on the nitrogen shield is ignored.

2. The temperature of the contents, nitrogen, is taken to be $-346^{o}F$. The largest gas conduction heat flux is obtained using the boiling temperature of liquid nitrogen at 1 atm abs.

3. The dewar, magnet and internal piping is assumed to be full of nitrogen.

4. The temperature of the exiting nitrogen flow is taken to be $60^{o}F$.

5. The heat flux into the nitrogen due to oxygen condensing is ignored.

6. The thermal conductivity at $100^{o}F$ is used, because thermal conductivity decreases with decreasing temperatures.

System Parameters

Total surface area of dewar, magnet and internal piping $= 25{,}000\ in^2$ maximum $= 173.6\ ft^2$

Description of Failure Modes

The loss of insulating vacuum can occur in two ways: (1) a leak in the inner vessel and/or internal piping, with the outer vacuum shell remaining intact, allowing nitrogen to infiltrate the multilayer insulation up to a pressure determined by the relief device on the vacuum space and (2) a leak in the vacuum shell, which allows air to infiltrate the multilayer insulation up to 15 psia. The former produces a heat flux to the liquid nitrogen through nitrogen gas conduction. The latter produces a heat flux to the liquid nitrogen due to ambient air gas conduction.

Calculations

Heat load due to gas conduction from NBS Monogram 111, "Technology of Liquid Helium" pg. 289:

$$q = UA\,(100-t)$$

where

$$U = \text{thermal conductance} = \frac{\text{thermal conductivity}}{\text{insulation thickness}}$$

A = surface area of vessel

t = temperature of the contents

$= -346^{\circ}F$

U for ambient air at 100°F

$$K = 0.2686\ \frac{mW}{cm\text{-}K}$$ ("Cryogenic Engineering" R.B. Scott)

$$= 0.01552\ \frac{BTU}{Hr\text{-}ft\text{-}^{\circ}F}$$

Y = thickness of insulation

$= 3/12 = 0.25$ ft

$$\therefore U = 0.06208\ \frac{BTU}{Hr\text{-}ft^{2}\text{-}^{\circ}F}$$

U for nitrogen at 100°F

$$K = 0.0156\ \frac{BTU}{hr\text{-}Ft\text{-}^{\circ}F}$$ ("Engineering Heat Transfer" Karlekar)

$Y = 3/12 = 0.25$ ft

$$U = 0.0624\ \frac{BTU}{Hr\text{-}ft^{2}\text{-}^{\circ}F}$$

Heat load due to ambient air conduction

$$q = (173.6)(0.06208)[100 - (-346)]$$

$$= \underline{4{,}806}\ W$$

Heat load due to nitrogen gas conduction

$$q = (173.6)(0.0624)[100 - (-346)]$$

$$= \underline{4,831}\ W$$

Generalized sizing of relief

The basic equation for sizing relief devices is

$$Q_a = \frac{13.1\ WC_a}{60\ C}\left[\frac{ZTM_a}{MZ_aT_a}\right]^{1/2}$$

W = lb/hr, required flow of the gas = g/L

L = Latent heat (BTU/lb)

C_a = Gas constant = 356 for air

C = Gas constant of the gas

Z_a = Compressibility factor = 1.0 for air at STP

Z = Compressibility factor for the gas at the flow condition

M_a = Molecular weight of air = 28.97

M = Molecular weight of the gas

T_a = Temperature of air at STP = 520 R

T = Temperature of the gas at the flow condition.

Substituting the values for C_A, M_A, Z_A and T_A and replacing HA by q, the heat load on the inner vessel,

$$Q_A = \frac{18.3\ q}{CL} \quad \frac{ZT}{M}^{\ 1/2}$$

For nitrogen gas

$C = 356,\quad Z = 1.0,\quad M = 28$

$$\therefore Q_A = \frac{(18.3)}{356} \times g/L \times \left[\frac{T}{28}\right]^{1/2}$$

$$Q_A = (0.0097)(q/L)(T)^{1/2}$$

Assumptions

1. Pressure of venting nitrogen = 20 psia.

2. The temperature of the flowing, exiting, gas is 520°R.

Sizing criterion for 20 psia venting

L at P = 20 psia ≈ 85 Btu/lb

$$Q_A = \frac{(0.0097)(520)^{1/2}}{85} \quad q$$

$$Q_A = (0.0026)\ q$$

sizing of relief for nitrogen gas conduction.

$$Q_A\ (N_2 \text{ conduction}) = (0.0026)(4{,}831)$$

$$= \underline{12.4} \text{ SCFM-air at } 60^{\circ}\text{F}$$

sizing of relief for ambient air conduction

$$Q_A\ (\text{ambient air conduction}) = (0.0026)(4{,}806)$$

$$= \underline{12.4} \text{ SCFM-air at } 60^{\circ}\text{F}$$

Installed Relief Valve

The helium dewar has the following three relief devices.

1. 4" Fike rupture disk; set pressure = 20 psig.

2. 1" 200 series Circle Seal; set pressure = 5 psig. Check valve model 280, flow capacity = 130 SCFM of air if the valve is open to atmosphere, with a 5 psi pressure drop across the valve.

3. 1-1/4" 200 series Circle Seal; set pressure = 8 psig, check valve model 280.

The capacity of the 1" 200 series Circle Seal check valve is sufficient to handle the above mentioned failures separately, nitrogen gas conduction or ambient air conduction.

Conclusion

Nitrogen precooling of the helium space will not produce high pressures in the helium dewar unless it is done rapidly. The single Circle Seal check valve set at 5 psig that vents outside will be sufficient to handle the gas produced when the liquid nitrogen is vaporized due to a loss of vacuum, either through nitrogen gas conduction or ambient air conduction. In the failure mode where the vacuum shell has a leak, there can be a small amount of heat flux produced when oxygen condenses against the helium dewar inner vessel; the additional nitrogen gas that is produced can be handled by the excess capacity of the 1" Circle Seal check valve. Barron in his book "Cryogenic Systems" pg. 504 shows that the heat flux into a bare liquid oxygen line due to convection is 575 Btu/hr-ft^2 and the heat flux into a bare liquid hydrogen line due to convection and condensation is 3,500 Btu/hr-ft^2. Therefore, condensation, ignoring the increased convection heat flux due to the lower temperature of the hydrogen, can increase the heat flux experienced by a cryogenic line and/or vessel by a factor of approximately six. For the worst case the flow capacity of the relief device must be six times higher than calculated for just ambient air conduction. The flow capacity of the 1" Circle Seal check valve is ten and a half times higher than the flow capacity required for ambient air conduction.